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ADVANCED JET ENGINE COMBUSTOR TEST FACILITY

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| 16. Abstract <p>A test facility for conducting full-scale advanced annular jet engine combustor research and durability tests is described. Combustors have been operated on ambient or heated ASTM-A1, natural gas, and propane fuels to an average exit temperature of 2400° F (1589 K). The airflow of 285 lb/sec (129.4 kg/sec) at 1200° F (922 K), 115 psia (79.2 N/cm²), and 60 000-ft (18 240-m) altitude exhaust capability allows simulation of combustor inlet conditions over most of the range of interest in supersonic cruise engines. Description of a unique jet-engine-fired, nonvitiating air heater is included. The test section, the instrumentation, the data acquisition system, and operation techniques and experiences are also described.</p> | | | |
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SUMMARY

This report is a general description of a test facility for investigating problems associated with advanced jet engine combustors. The problems of altitude relight, acceleration, durability, and smoking are investigated. During the past three years, one combustor was given a 325-hour endurance test at typical advanced supersonic aircraft conditions. Four other combustors, operating concurrently, have accrued over 575 research hours on more than 100 different configurations.

The facility contains a 285-pound-per-second (129.4-kg/sec), 1200⁰ F (922 K) non-vitiating air heater system. This system utilizes two heat exchangers fired by jet engines with afterburners. The jet engines were converted to operate on natural gas to minimize pollution of the surrounding environment. Over 1200 hours of successful operational experience has been logged with this equipment.

Test combustors are operated in full-scale throughout the range of conditions (except takeoff) of advanced supersonic aircraft to Mach 3, 60 000-foot (18 240-m) altitude, and average exit temperatures of 2400⁰ F (1589 K). The capability of operating at higher exit temperatures is being added. Temperature-conditioned fuels are available as follows: natural gas to 1200⁰ F (922 K), propane to 250⁰ F (394 K), and ASTM-A1 to 750⁰ F (672 K). Descriptions of the test section, air handling system, fuel systems, data acquisition systems, and operational techniques and experiences are included.

INTRODUCTION

The quest for increased speed and payload in aircraft over the past decade has brought about significant advancement in turbojet engine characteristics such as specific thrust, specific weight, and specific fuel consumption. These advancements have been achieved, mainly, by increasing the airflow per square foot of frontal area, the compressor stage pressure ratio, and the turbine inlet temperature, and by weight reduc-

tion. The next generation of engines demands even further advancements in these areas without compromise to engine durability.

To the combustor this means operating at higher temperatures and pressures. Because high combustion efficiency is relatively easy to attain at elevated temperatures and pressures, the principal combustor problems are combustor durability and exit temperature profile.

A reduction in engine weight and length can be achieved through the use of a shorter combustor. A short combustor length increases the difficulty of attaining a uniform exit temperature profile. In addition, the combustor inlet diffuser becomes a significant fraction of the total combustor length and must be the subject of careful design and testing in order to achieve this desired short overall combustor length.

Experience has shown that tests of diffuser and combustor segments do not always duplicate the flow phenomena observed in full-annulus tests. Also, it has been found that combustors cannot be reliably scaled. Only full-scale, full-annulus testing provides the three-dimensional flow field required for development and endurance testing of short, integrated combustors and diffusers. The required facility airflow, pressure, and temperature levels are determined from the maximum envelope of advanced engines under consideration. By utilizing the available laboratory airflow and pressure capabilities, all but sea-level static takeoff conditions of advanced supersonic engines can be simulated. The use of a combustor to heat the inlet air to the desired temperature would reduce the oxygen concentration and decrease the combustion efficiency (refs. 1 and 2). Therefore, provision was made to heat the air indirectly by means of heat exchangers.

Flexibility and durability of the test facility are significant requirements. Combustor research and development includes many cut-and-try approaches. This demands quick installation and testing. Combustors must be made interchangeable and easy to handle. Provision for temperature-conditioned natural gas, propane, and ASTM-A1 provides a wide selection of fuels for investigation of combustion characteristics. The facility components are designed and built to withstand large thermal gradients over many cycles of operation and to cover a wide range of operating conditions. The facility is also designed for ease of operation with a minimum number of personnel.

GENERAL DESCRIPTION

The combustor test facility occupies one-half of the Engine Components Research Laboratory at Lewis Research Center, shown in figure 1. This building houses two test cells approximately 60 feet (18.3 m) long by 22 feet (6.7 m) wide and 22 feet (6.7 m) high, two control rooms, and a small shop space. The cells are constructed with walls of 1-foot- (0.31-m-) thick reinforced concrete and a blowoff-type roof.

The facility incorporates the following systems: combustion air system for providing the desired pressure and flow rates; combustor fuel systems that will deliver either liquid or gaseous fuel at the desired pressure and temperature; a supplemental non-vitiating heater system that can raise the temperature of the test air to 1200° F (922 K); an exhaust gas quench and jacket water cooling system; a fire and safety protection system; and a test combustor cooldown system. The control room has three control stations: one for the test combustor, a second for combustion air and water supply, a third for supplemental air and fuel heaters, and a fourth station for continuous research information readout.

The facility has been used for two modes of combustor operation—endurance and research testing. Endurance testing is accomplished by cycling the test combustor on and off while the inlet air temperature is held constant. A typical cycle consists of lighting the combustor and operating for 1 hour at a condition simulating either takeoff, climb, or cruise. It is then shut down for 5 minutes and the cycle is repeated. Sufficient cycles of each condition are run to be representative of the intended flight service conditions. By running calibration points at the beginning and end of a group of cycles, the combustor instrumentation will indicate any performance degradation as the test progresses. Periodic, visual inspections reveal whether the combustor is safe for continued operation.

Research testing is accomplished by comparing the performance of different combustor configurations at predetermined operating conditions. When a combustor shows promise, these conditions are expanded to include an altitude relight map and combustor response tests. The latter test demonstrates how quickly a combustor will convert the fuel into temperature rise, simulating an engine acceleration.

The flow path and the arrangement of the major components of the combustion air system are shown in figure 2. The test combustor and adjacent ducting are shown in figures 3(a) to (c). The combustion air is heated to a maximum of 600° F (589 K) in an outside preheater and is delivered to the cell through a 36-inch- (91.5-cm-) diameter ASME orifice run. Upon reaching the test cell, the air can be delivered to the test combustor or it can be passed first through heat exchangers having the capacity to heat the air to 1200° F (922 K). Fixed probes at the test combustor entrance measure the inlet temperature and pressure profiles. The exit temperature and pressure profiles are measured with three circumferentially traversing probes located on a drum in the instrument section.

The combustor airflow rate and pressure are set with an inlet valve and an exhaust valve. A removable choke plate may also be utilized downstream of the exit temperature probes to simulate a turbine. Before entering the exhaust valve, the hot gas is cooled to 180° F (355 K) by a series of quench water sprays. Cooling tower water is used for quench sprays and for cooling-water-jacketed parts of the instrumentation section.

Beyond the exhaust valve, the gas flows into the central atmospheric or altitude exhaust system.

The facility piping is arranged so that the test section may be cooled after completion of a run either with unheated combustion air or with the ventilation system air, or by using the altitude exhaust system, as shown in figure 2. During this process, the supplemental heaters are bypassed so they can cool slowly, minimizing thermal stresses in the heaters and the related piping.

SUPPLEMENTAL AIR HEATERS

The facility requirement to heat 285 pounds of air per second (129.4 kg/sec) at 115 psia (79.2 N/cm^2) to 1200° F (922 K) is accomplished in two stages. A central system outside preheater is used for heating the air to 600° F (589 K). The supplemental stage of heating up to 1200° F (922 K) is done in two shell-and-tube heat exchangers operating in parallel, each fired by a modified J-57 jet engine equipped with an afterburner, as shown in figure 4 (refs. 3 and 4); without afterburner and outside preheater, the supplemental heaters can provide inlet-air temperatures of 600° F (589 K).

Each supplemental heat exchanger (fig. 5) consists of a bundle of 639 stainless-steel tubes (ASTM A-249) each having an outside diameter of 1.5 inch (3.8 cm), a wall thickness of 0.083 inch (2.1 mm), and a length of 31.5 feet (9.6 m). The tubes are spaced at a 1.875-inch (4.8-cm) pitch triangular pattern, rolled, and welded at each end to the tube sheet. The outer cylindrical pressure shell is made of 3/4-inch (1.9-cm) ASTM A-240 stainless steel. An expansion joint is provided in the shell to accommodate the relative movement between the tube bundle and the shell caused by temperature differences. The tubes are intermittently supported by baffles (fig. 4) which are tie-bolted to the rear tube sheet. Sufficient clearance is provided to permit the tubes to move relative to the baffles. The engine-afterburner exhaust gases flow through the tubes, while the combustion air flows in the opposite direction in the shell parallel to and across the tubes (fig. 4).

In designing the heat exchanger, tube sizes, lengths, and spacing were optimized for utilizing the available pressure losses to achieve maximum overall heat-transfer coefficients. Its performance is shown in figure 6. This indicates an overall heat-transfer coefficient of $29.3 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ \text{F})$ ($60.0 \text{ J}/(\text{hr})(\text{cm}^2)(\text{K})$) at the design flow rate of 142.5 pounds per second (64.7 kg/sec). This is 5 percent lower than the design overall coefficient of $30.7 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ \text{F})$ ($62.8 \text{ J}/(\text{hr})(\text{cm}^2)(\text{K})$).

The afterburner consists of six symmetrical segments which form two concentric annular V-shaped gutters interconnected with six radial gutters (fig. 7). This segmented construction facilitates maintenance. The gutters are made of type-316 stainless-steel

sheets welded to a pipe at their apex. The pipes in each gutter serve as fuel manifolds. Natural gas from the 50-psig (34.5-N/cm^2) central distribution system is injected through orifices drilled in the pipe manifolds. The afterburner is lit by two small pilot burners located upstream and in line with the outer gutter.

The afterburner is designed with a capability to raise the engine exhaust gas temperatures as much as 600°F (589 K). Because of heat-exchanger tube sheet material limitations, an average inlet gas temperature upper limit of 1500°F (1089 K) is imposed with permissible spot variations of $\pm 100^{\circ}\text{F}$ ($\pm 55\text{ K}$). The engine and afterburner combination can raise the combustion air temperature at the nominal rate of 80°F (44 K) per minute.

The conversion of the engines and afterburner to use natural gas rather than jet fuel was prompted by considerations of cleanliness and operating economy. The test cell is located among a close complex of office buildings and adjacent to one of Cleveland Hopkins Airport glide paths where the use of tall exhaust stacks to disperse the pollutants is prohibited. Therefore, natural gas was selected because it burns cleanly and does not pollute the surrounding air with soot and odor as does jet fuel. The operational savings from using natural gas rather than jet fuel amount to \$186.00 per hour.

The engine conversion to natural gas necessitated using a compressor to boost the gas pressure from the normal 50 psig (34.5 N/cm^2) to 250 psig (172.5 N/cm^2). The liquid fuel control system was replaced with a modified commercial remote electric control system for gas operation. The J-57 diffuser section had to be modified to accept a new internal gas manifold with new fuel nozzle tips and a new exterior manifold. Standard combustor liners were used, but their durability was further enhanced by addition of more wear pads and by flame hardening the mating contact surfaces.

FUEL SYSTEMS

The facility provides a choice of three fuels for the combustors - ASTM-A1 jet fuel, natural gas, and propane at the following conditions:

| Combustor fuel | Maximum pressure | | Maximum flow rate at 80°F (300 K) | | Temperature range | |
|----------------|------------------|-----------------|--|--------|--------------------|------------|
| | psig | N/cm^2 | | | $^{\circ}\text{F}$ | K |
| | | | lb/sec | kg/sec | | |
| ASTM-A1 | 1000 | 690 | 3.8 | 1.7 | 80 to 300 | 300 to 422 |
| | | | 10.2 | 4.6 | 80 to 750 | 300 to 672 |
| Natural gas | 350 | 241.5 | 5.3 | 2.4 | 80 to 1200 | 300 to 922 |
| Propane | 625 | 432 | 1.04 | 0.47 | 80 to 250 | 300 to 394 |

A natural-gas-fired heat exchanger is used for heating either natural gas combustor fuel to 1200° F (922 K) or jet fuel, type A-1, to 750° F (672 K). Steam is also utilized for heating jet fuel to 300° F (422 K) and propane to 250° F (394 K).

All these systems include pumps, filters, and separators to provide a clean and water-free supply of fuel. For facility safety, all fuel systems are electrically interlocked with cell ventilation, research combustor overtemperature, loss of cooling water, combustor blowout, excess fuel flow, and loss of electrical power.

TEST SECTION

The test section shown in figure 8(a) consists of the following components: an inlet elbow with cooldown port, a straightening cone, a perforated flat plate, a constant-diameter straight section, a spool piece, a test combustor section, an instrument section, a transition piece, and an exhaust section. These components are mounted on rails that provide the necessary expansion and handling capabilities.

The design of the test combustor and the instrument section is covered in reference 5. The flow straighteners create a uniform airflow velocity profile at the inlet of the test combustor section. The perforated cone and flat plate have approximately 40 percent open area and are located at the inlet and exit of the elbow (fig. 8(a)).

The radial discharge profiles of advanced jet engine compressors are simulated by installing screens in the airflow annulus ahead of the combustor. The proper combination of mesh and radial extent of circumferential screen produces the desired radial flow profile. The screens are held in the positions shown in figure 8(b) either by attaching them to the combustor housing wall or by sandwiching them between combustor flanges. The uniformity of combustor-inlet temperature and airflow is measured by eight inlet thermocouples T_{t3} , eight total-pressure probes P_{t3} , and 16 static-pressure probes P_{s3} located every 45° circumferentially about the outer and inner walls of the test combustor housing, as shown in figures 8(b) and (c). The combustor exit total temperatures T_{t5} and total pressure P_{t5} are measured by three water-cooled probes evenly spaced on a water-jacketed drum. The drum may be rotated 120° in either direction by an electric motor in the water-jacketed instrument section. The exit probes (figs. 9(a) and (b)) are positioned in the plane typical of the first-stage turbine stator of an engine (fig. 8(b)). The five temperature and pressure pickups on each probe are located radially at the center of equal annulus areas.

Besides providing combustor exit temperature and pressure measurement capability, the instrument section includes the exhaust quench water system and water-cooled choke plates. This section is designed to handle combustors with average exit temperatures of

2400⁰ F (1589 K) with hot streaks of not more than 2700⁰ F (1755 K). Fabrication is now in process to obtain a system that will raise both of these levels by 1000⁰ F (555 K).

To achieve the greatest test facility utilization, each research program is designed to use interchangeable test combustor sections that fit quickly into the facility. These sections, with spacers, will accommodate changes in combustor length. Some sections will also accept interchangeable diffuser assemblies. Spare combustor and diffuser components allow modifications to be accomplished while alternate assemblies are being tested. Figure 10 shows two of the test combustor sections in buildup. Figure 11 shows the test section about to receive a test combustor. Opening the rail facilitates the installation of the test combustor. The position of the exit probes on the rotatable drum can also be seen in this figure.

INSTRUMENTATION SYSTEMS

The following tabulation shows the current data channels provided for facility operation and test combustor measurements;

| Instrumentation | Number of channels |
|--|--------------------|
| Strain gage - pressure or displacement | 64 |
| Pressure | 290 |
| High-frequency pressure | 6 |
| High temperature - 3000 ⁰ F (1921 K) | 48 |
| Medium temperature - 100 ⁰ to 2200 ⁰ F (355 to 1478 K) | 304 |
| Turbine-type flowmeter | 12 |
| Oscillograph | 48 |
| Temperature profile monitoring | 40 |

The research data for the combustor test facility are recorded automatically by the central data recording systems. In addition, some of these data, along with facility operational data and prerun checkout information, are recorded on separate recording equipment contained in the test cell control room. Figure 12 is a simplified block diagram of the flow of data from the test apparatus to the recording equipment. Disconnect boxes, cabling, terminal strips, and signal conditioning equipment are used as required. Patchboards are used to conveniently route the various input channels into the proper recording equipment, and to check out equipment, amplifiers, or control room visual

displays. The various types of transducer systems and data recording systems are described in the following sections.

Data Acquisition and Signal Conditioning Systems

A 64-channel strain-gage system is provided for measuring differential pressures, nonpneumatic pressures, and the angular and linear positions of probes. Forty-eight channels are used for research data and 16 channels for monitoring facility operating conditions. The pressure transducers used in this system are 350-ohm, eight-wire, shunt-calibrated, commercially available strain-gage-type transducers. The system also incorporates bridge completion networks for use with linear taper resistance potentiometers to indicate probe position.

Each strain-gage channel is provided with an individual signal conditioning module and integral power supply designed and constructed to permit its use with one, two, and four active-arm transducers. Channel calibration is accomplished by shunting a 100 000-ohm potentiometer across one arm of the transducer. The overall accuracy of the transducer system is within ± 0.52 percent of full scale.

The Digital Automatic Multiple Pressure Recorder (DAMPR) system (ref. 6) is used to record pneumatic pressures measured at the research installation or at the support systems. Up to 290 pressures can be routed from the test hardware through copper tubing to this system. In addition, 30 channels of system calibration data are provided for data reduction purposes. The system can handle pressures from 0.35 to 190 psia (0.24 to 131.0 N/cm²) accurate to 0.1 percent of full scale. A further discussion of DAMPR is given in the section Data Recording and Monitoring Systems.

A six-channel high-frequency pressure measurement system is utilized to acquire dynamic pressure data over a frequency range of steady-state to 5000 hertz. The system can resolve recorded pressures to within 5 percent of full scale and frequencies to within ± 2 hertz. The system is composed of piezoelectric-type transducers, charge amplifiers, and the associated coaxial cabling.

The temperature measuring system for the test cell provides for iron-constantan, Chromel-Alumel, and platinum/platinum-13-percent-rhodium thermocouples to cover the range from ambient to 3000° F (1921 K). The system consists of 192 channels that are routed through four 48-channel reference ovens and an additional 160 alloy channels. The channels that utilize the reference ovens are used both for research data and for monitoring facility operating conditions. The alloy channels are used solely for facility monitoring. The reference ovens are maintained at a constant temperature of 150° F (339 K) with a temperature stability of ± 0.25 ° F (± 0.14 K). The overall accuracy of the Chromel-Alumel and iron-constantan channels is within ± 0.4 percent of reading. The

overall accuracy of the platinum/platinum-13-percent-rhodium channels is within ± 0.29 percent of reading.

Turbine-type flowmeters are used to produce frequency signals proportional to fluid flow rates. This 12-channel system utilizes the alternating-current (ac) outputs of the transducers by feeding them into frequency converter modules which convert the ac signal to an analog direct-current (dc) voltage proportional to the frequency of the ac signal. The converter modules also generate a rectangular wave ac output that is utilized for control room frequency counter digital readouts. A calibration module is an integral part of the system and provides appropriate precision frequencies that are used for recording system calibration. The overall accuracy of the transducer system is within ± 0.62 percent of full scale.

Combustor Exit Probe

A traversing probe system is used to survey the exit total temperature profile of the gas stream immediately downstream of the test combustor. This survey is made by traversing the three evenly spaced probes through 120° travel in 3° steps, thereby obtaining a complete 360° map of combustor exit temperature. Approximately 7 minutes are required to complete this traverse survey.

The probe is positioned out of the gas stream behind three water-cooled probe shields when data are not being taken; this position is referred to as the "home" position. These home positions minimize the time the probe is exposed to the gas stream environment, thereby extending the life of the probe. When a data point is to be taken, the probe control system is operated manually to the first data position and the automatic data recording sequence is initiated. When the data recording is complete for the first probe position, the probe actuator control automatically advances the probe to the next circumferential position and the data are again recorded. This sequence of events is repeated automatically until the data are obtained at all circumferential positions. The probe is then automatically run until it comes to the next home position, which is 120° from its starting point. During the next data point sequence, the probe is run in the opposite direction and, upon completion of this point, ends up in the original home position. By utilizing the automatic probe control and multiple probe heads, the recording time of the laboratory central digital recording system is minimized and the useful life of the test hardware is extended.

Data Recording and Monitoring Systems

An analog recording system (fig. 13) provides a record of selected steady-state-

and transient-type data. This system is also used to facilitate prerun checkout and to provide data recording for small test programs that do not lend themselves to the central recording system. Four 24-channel oscillograph recorders and their associated input conditioners and four 24-point temperature recorder indicators are provided in this system.

The Lewis Research Center has a Central Automatic Digital Data Encoder (CADDE) system (refs. 6 and 7) that is available to all large research facilities to automatically record steady-state data. CADDE incorporates a small general-purpose digital computer that is capable of recording as many as 500 voltages and 500 pressure measurements. Voltage measurements are sequentially recorded at a rate of about 20 samples per second. All pressures are recorded during a 10-second interval. The CADDE system in this test cell is composed of two "subsystems:" one a 200-channel Automatic Voltage Digitizer system (AVD), and the second a 320-channel Digital Automatic Multiple Pressure Recorder system (DAMPR). The AVD portion of the system, which is used to record thermocouple, strain-gage and position transducer, and turbine-type flowmeter outputs, is capable of recording voltages to 100 volts accurate to within ± 0.038 percent of full scale. The DAMPR range and accuracy are as stated in the section Data Acquisition and Signal Conditioning Systems. An automatic typewriter and facsimile plotter located in the control room provide a record of the raw data.

The CADDE data system is connected to an IBM 360, Model 67, time-shared computer. A time-sharing typewriter terminal which is part of this system is located in the test cell control room. This system enables the central computer to provide computed test results as well as instrumentation channel checks to the test facility within minutes of recording. In most cases, all the information available from this system is in engineering units. The operation and description of this system is given in reference 8.

The 200-channel Scanner/Digital Volt-ohmmeter system is used to perform prerun checkout for the research instrumentation. The system also provides a printed record of strain-gage transducer "zero" and full-scale calibrations. The primary patchboard is used to transfer all the selected channels and calibration signals into this system.

Combustor testing usually involves the determination of exit temperature profiles. To present a comprehensive monitoring display of temperature profiles, a bar-graph-type profile monitor is used (fig. 13). This profile monitor is capable of displaying 40 channels of temperature data on a 12-inch (30.5-cm) cathode ray tube in engineering units by means of a calibrated electronically produced grid. In operation, each channel is presented as a solid vertical "bar" of light, the height of which is directly proportional to its input signal level. The unit also contains an integral alarm circuit that intensifies the display of any channel that exceeds a predetermined limit, and simultaneously activates a relay that is used as an abort shutdown.

Operational Experience

Just the more significant and unique operational experiences over the past three years are reported. Initially, the facility warmup time was established by limiting thermal gradients in the heaviest flange in the system. This flange was located at the discharge of the test-section inlet elbow, as shown in the insert in figure 8(a). To accelerate the warmup, electrical preheat was applied to maintain acceptable thermal gradients in this flange. This produced what was known as a standard facility warmup rate; however, after 79 operating cycles with this criterion, extensive cracking was found in the heat-exchanger discharge pipe.

These cracks occurred in the pipe wall adjacent to the gimbal ring welds. Figure 14(a) shows a crack representative of those that appeared in 20 of the 24 quarter panels. These cracks, hidden by insulation, were not detected during routine inspection. Figure 14(b) presents the initial gimbal design with the torque rings attached to the pipe with full circumference weldments and stiffening plates between rings every 90° , dividing the surface into rigid quarter panels.

Heat-transfer calculations, later confirmed by test, showed that the standard $1\frac{1}{2}$ -hour warmup created a temperature differential between pipe wall and gimbal ring outer surface of 700° F (644 K). These heating curves and this temperature-differential are shown in figure 15. With extended operation and completely insulated gimbals, the rings approached the pipe wall temperature, so that on cooldown nearly the same temperature differential occurred, but in the reverse direction. It was concluded that the severe thermal gradients and their reversal caused the high-temperature cyclic fatigue of the $3/8$ -inch (0.95-cm) pipe wall adjacent to the ring weld.

After grinding out all the cracks and rewelding them, the following courses of action were instituted to prevent future failure:

- (1) As an interim measure, the gimbal rings were electrically heated and held to a maximum temperature differential of 250° F (139 K) between pipe wall and gimbal ring.

- (2) A piping modification was made that isolated the supplemental air heater system so that it could remain at high temperature while air was passed through the test section during cooldown.

The interim measure allowed further operation of the facility without cracking until gimbal replacement 179 cycles later.

A new gimbal design was initiated that eliminated the need for electrical heating and the severe temperature warmup limitation. This design is shown in figure 14(c). Analysis indicates that the unusual method (low-thermal-gradient cones) of attaching the ring to the pipe will allow warmup to 1200° F (922 K) in 20 minutes without any supplemental heating. This approximates the nominal supplemental air heater capability of 80° F (44 K) per minute.

Another problem was the cracking of the tube-to-tube sheet weld in the heat exchangers of the supplemental air heater system. The mechanism of failure and the crack progression rate have been difficult to determine. The loss of metered air through these cracks is important since it affects the measurement of combustor airflow. Figure 16 shows certain tubes, identified by stuffing them with paper, that have developed circumferential cracks in the seal weld between tubes and tube sheet. The insert in the corner is an enlargement of severely cracked tubes. However, not easily visible are the cracks that exist in the ligament areas between the tubes.

Four courses of action were instituted to minimize this problem:

- (1) Improving the afterburner temperature profile
- (2) Rerolling all the tubes in the tube sheet
- (3) Revising the piping, as previously discussed, to effectively isolate the heat exchanger from the test section cooldown airflow
- (4) Operating the supplemental air heater system at a volumetric flow rate of 45 percent of design value or higher to prevent channeled flow in the heat exchanger, thus maintaining nearly equal expansion of tubes

During initial checkout of the facility, an operational problem appeared. Depending on the severity of the winter weather, the J-57 engine operation was abruptly terminated after 10 to 30 minutes due to fuel starvation. The gas compressor is located remotely from the engines. Approximately 1000 feet (304 m) of uninsulated above-grade piping existed between the compressor and the test facility. Moisture in the gas, whose dew-point had been raised by compression from -40°F (233 K) to approximately 60°F (289 K), was condensed and frozen in the pipe and appeared as ice and snow on the engine filters. The problem was solved with proper water separators, new filters, insulation of the pipeline, and rearrangement of piping around the gas aftercooler and the surge tank to allow warmer gas to flow into the line, maintaining the gas above 32°F (238 K).

Over 1200 hours of nearly trouble-free operation has been experienced between the two engines. The only significant engine problem to appear was cracking around unused accessory mounting bosses on the compressor intermediate case. Replacement was made with cases incorporating two changes: internal stiffeners and deletion of all accessory bosses. Over 400 hours of satisfactory operation has since been logged.

Initial afterburner gas profiles spread as much as 225°F (125.0 K), as measured at the heat-exchanger tube sheet. This would not meet the initial design criteria of $\pm 100^{\circ}\text{F}$ ($\pm 55\text{ K}$). Through the use of blockage plates and redistribution of fuel, the profile is now within limits (fig. 17).

Operational experience with the afterburner shows it will light smoothly in the engine range of 65 to 80 percent speed. Light-off above 80 percent speed was found to be unreliable. Consequently, once the afterburner is normally lit at about 75 percent engine speed, both engine speed and afterburner fuel are increased slowly to bring the heat

exchanger and the engine to operating condition. At 92 to 94 percent engine speed, further increase in temperature is obtained by increasing only the afterburner fuel flow.

A nominal transient limit of 80°F per minute (44 K/min) has been established for supplemental heaters to prevent too great a spread in tube sheet metal temperatures. At steady state, the system holds the temperature of the heated air very stably, within $\pm 5^{\circ}\text{F}$ ($\pm 3\text{ K}$). Experience has shown the desirability of operating just one heat exchanger system when heated air flows are 142 pounds per second (64.7 kg/sec) or less.

Operational Procedures

The following general sequence of operation is followed with the new gimbals in the system when 1200°F (922 K) inlet-air temperature is desired:

(1) Two hours prior to the start of the test, calibration and setting the zeros and span of the instrumentation are begun.

(2) At test time with zero pressure and flow through the facility, an integrity check of the instrumentation is made and recorded. The central facility preheater is started and brought to standby conditions with the air heated to 300°F to 400°F (422 to 478 K) in a bypass mode.

(3) A leakage check of facility connection joints and flanges is made with 40-psig (27.5-N/cm^2) cold air from the cooldown system. While leaks are being corrected, another instrumentation integrity check is made at this pressure level.

(4) The cooling-water pumps are started but only jacket water is allowed to flow into the test section. Hot combustion air from the preheater bypass mode is then rerouted into the test section, followed immediately thereafter by adequate quench water.

(5) The warmup of the test section and test combustor is continued at an airflow rate of 80 to 100 pounds per second (36.3 to 45.3 kg/sec). When the inlet air at the combustor has reached approximately 600°F (589 K), the supplemental heater system is activated. The jet engines, afterburners, and heat exchangers finally bring the inlet air temperature to the desired operating level. Cooling-water adjustments are made, compatible with higher combustor inlet conditions.

(6) Once at proper inlet condition, the test section inlet and exhaust valves are adjusted to achieve the desired test combustor pressure and flow conditions. Another instrumentation integrity check is made and recorded. Now the test combustor is ignited and the test is started. Cooling water is adjusted to maintain safe limits during burning, warmup, and cooldown. Jacket water outlet temperatures are held below 150°F (339 K) and hot gases are quenched below 180°F (355 K) before entering the central facility exhaust system.

(7) The steps are reversed to cool down, except that once the afterburner and jet

engine are turned off, the cooldown flow leg is used to isolate the supplemental heater and to quickly reduce the test section to a safe handling temperature. This facilitates the combustor removal and installation of the next test combustor.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 30, 1970,
720-03.

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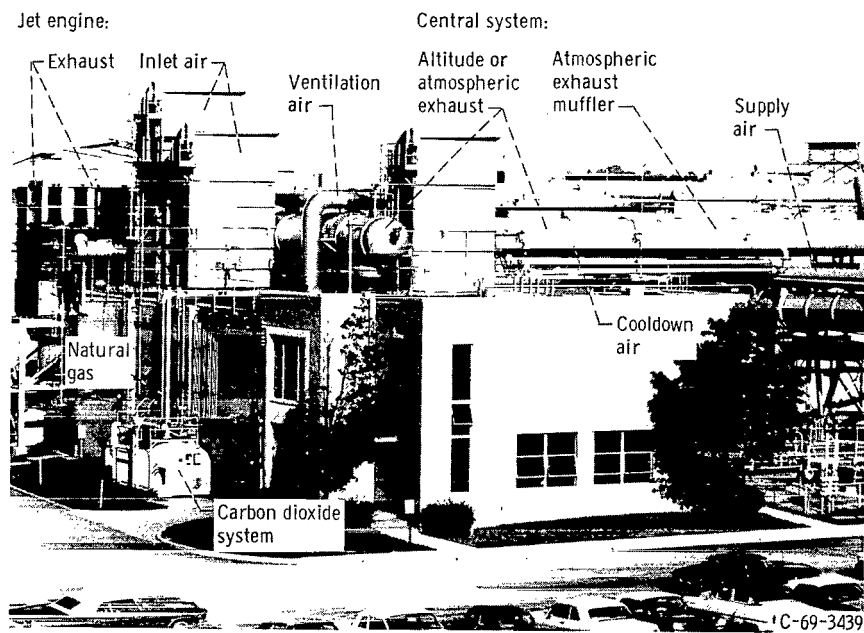
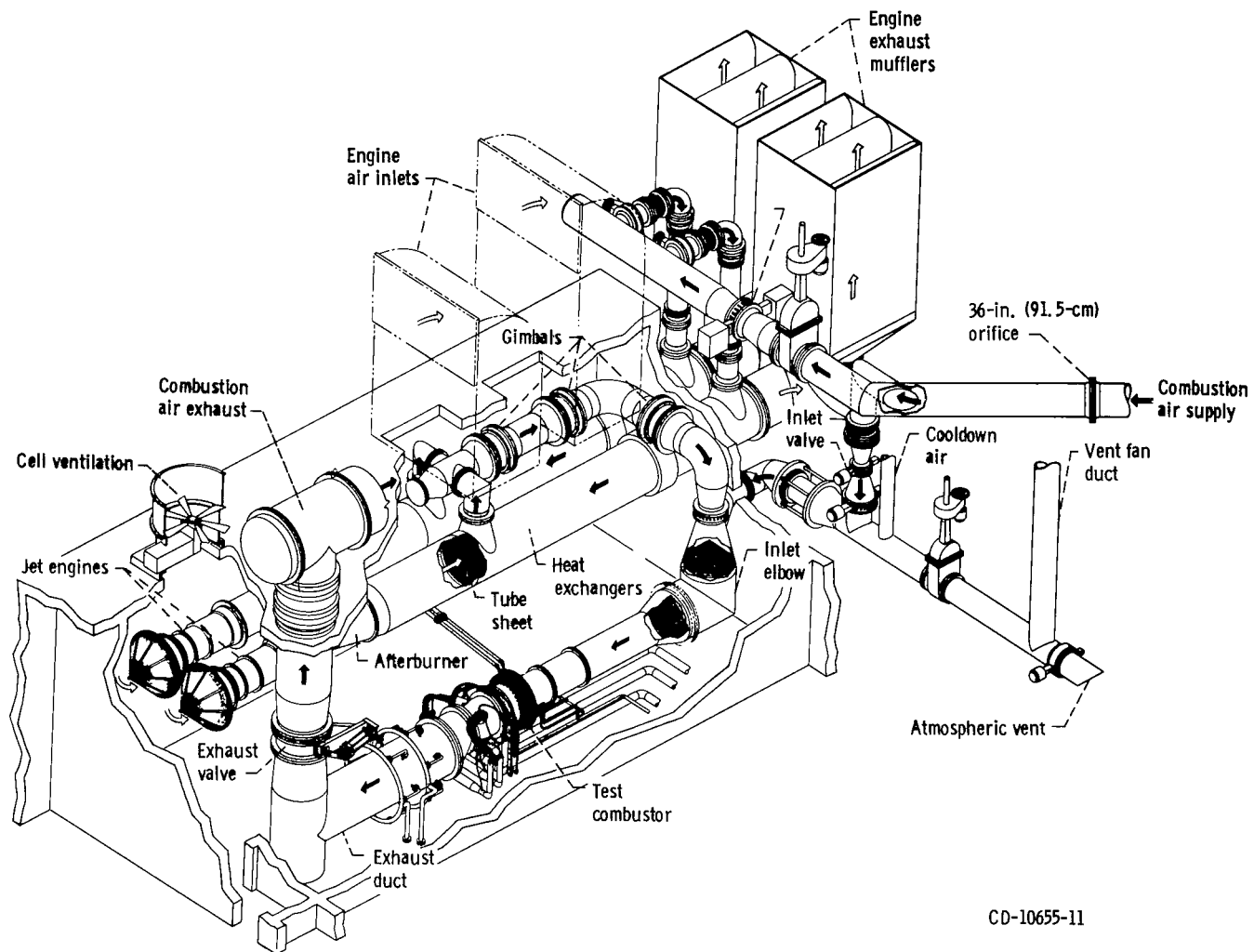
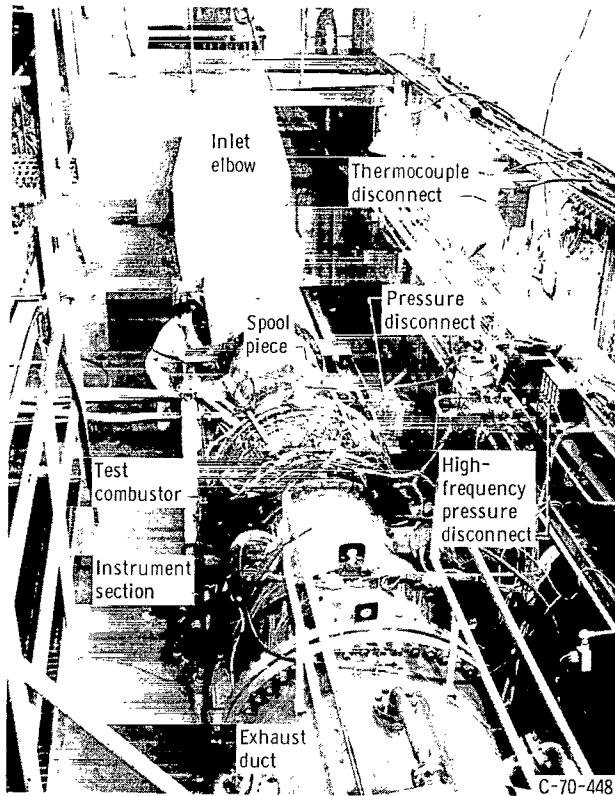


Figure 1. - Engine Component Research Laboratory.

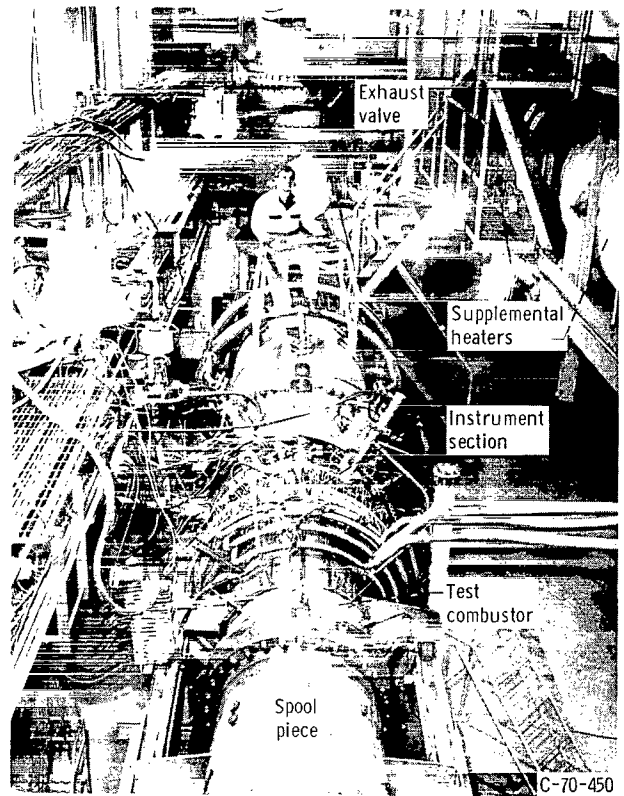


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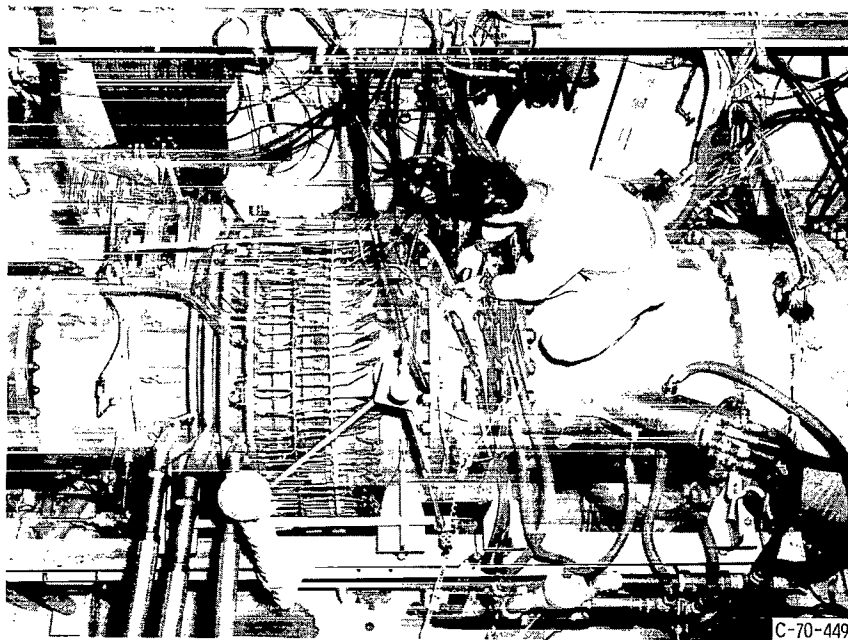
Figure 2. - ECRL-1 flow path and equipment arrangement.



(a) Looking upstream.



(b) Looking downstream.



(c) Test combustor and instrumentation section.

Figure 3. - Test cell interior.

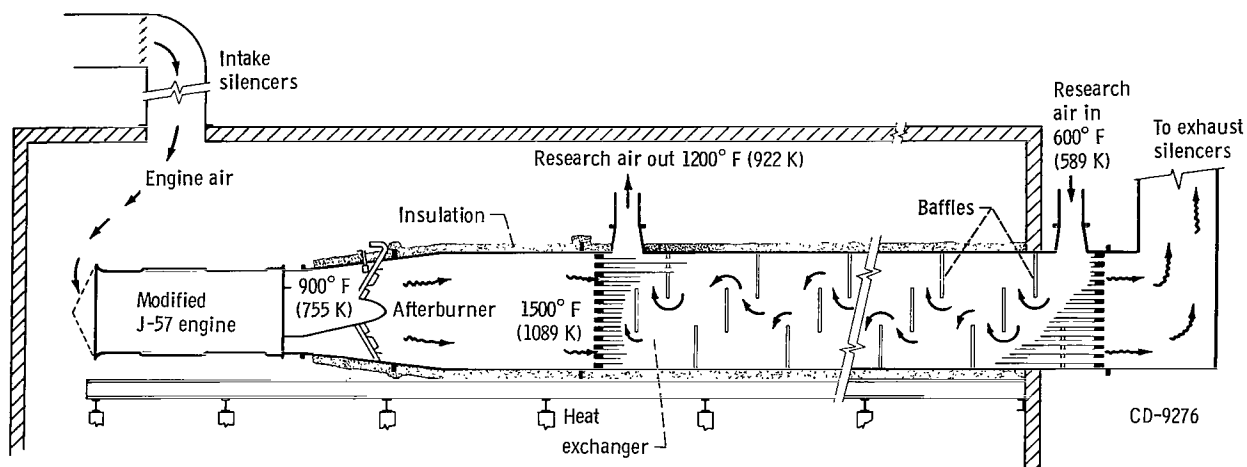


Figure 4. - Supplemental heater system.

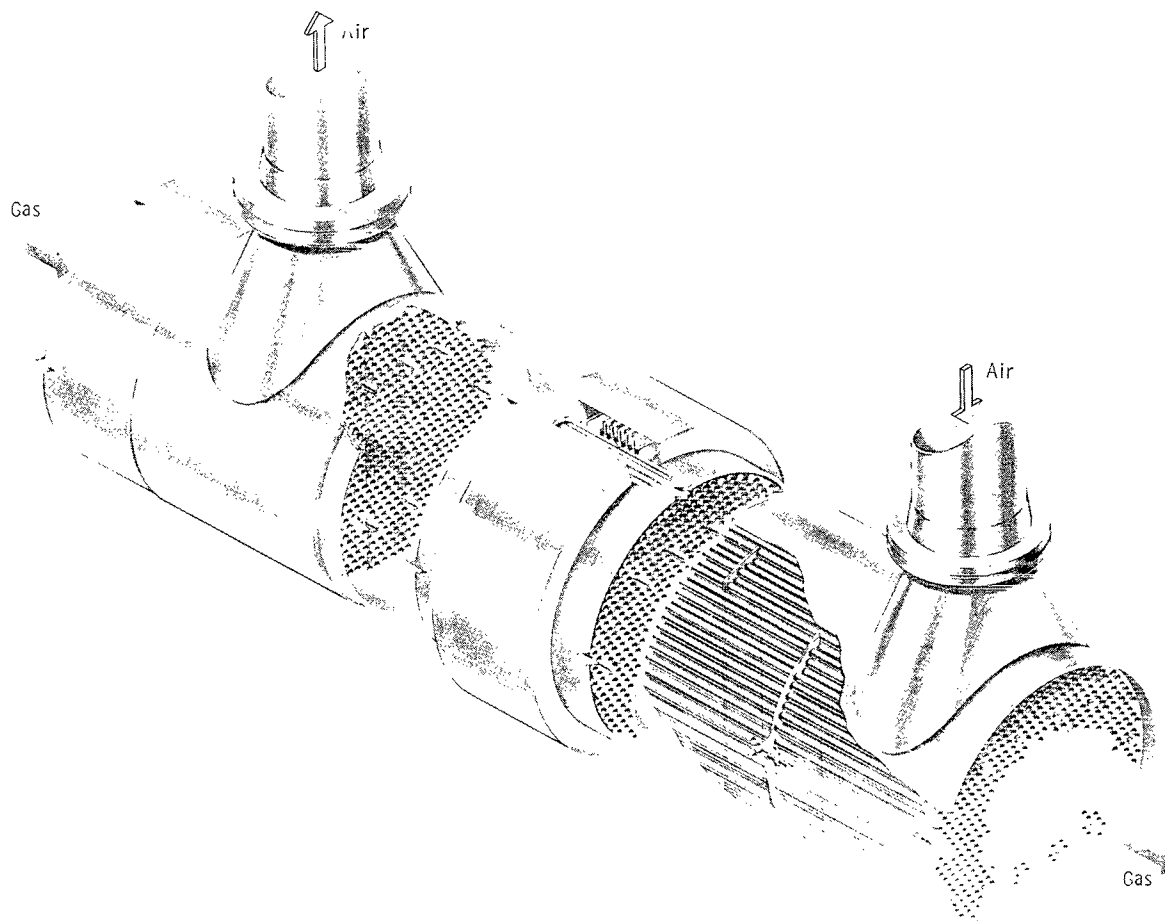


Figure 5. - Heat exchanger.

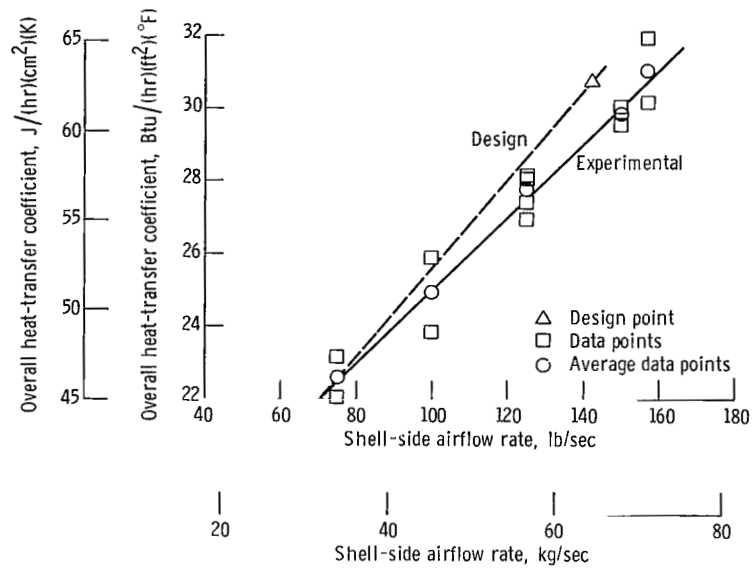


Figure 6. - Comparison of design and experimental overall heat-transfer coefficients with flue gas held at 145 to 155 pounds per second (65.9 to 70.5 kg/sec).

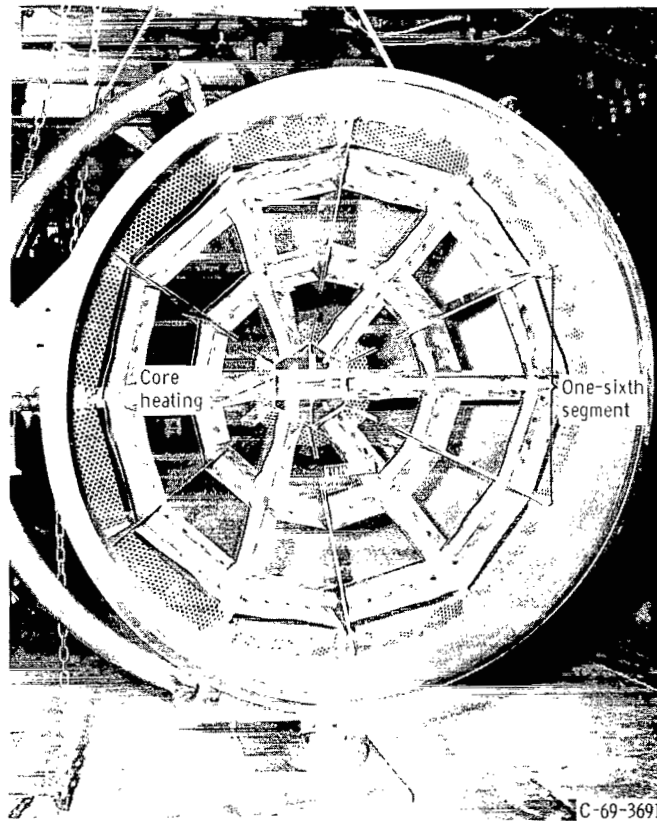


Figure 7. - Afterburner assembly.

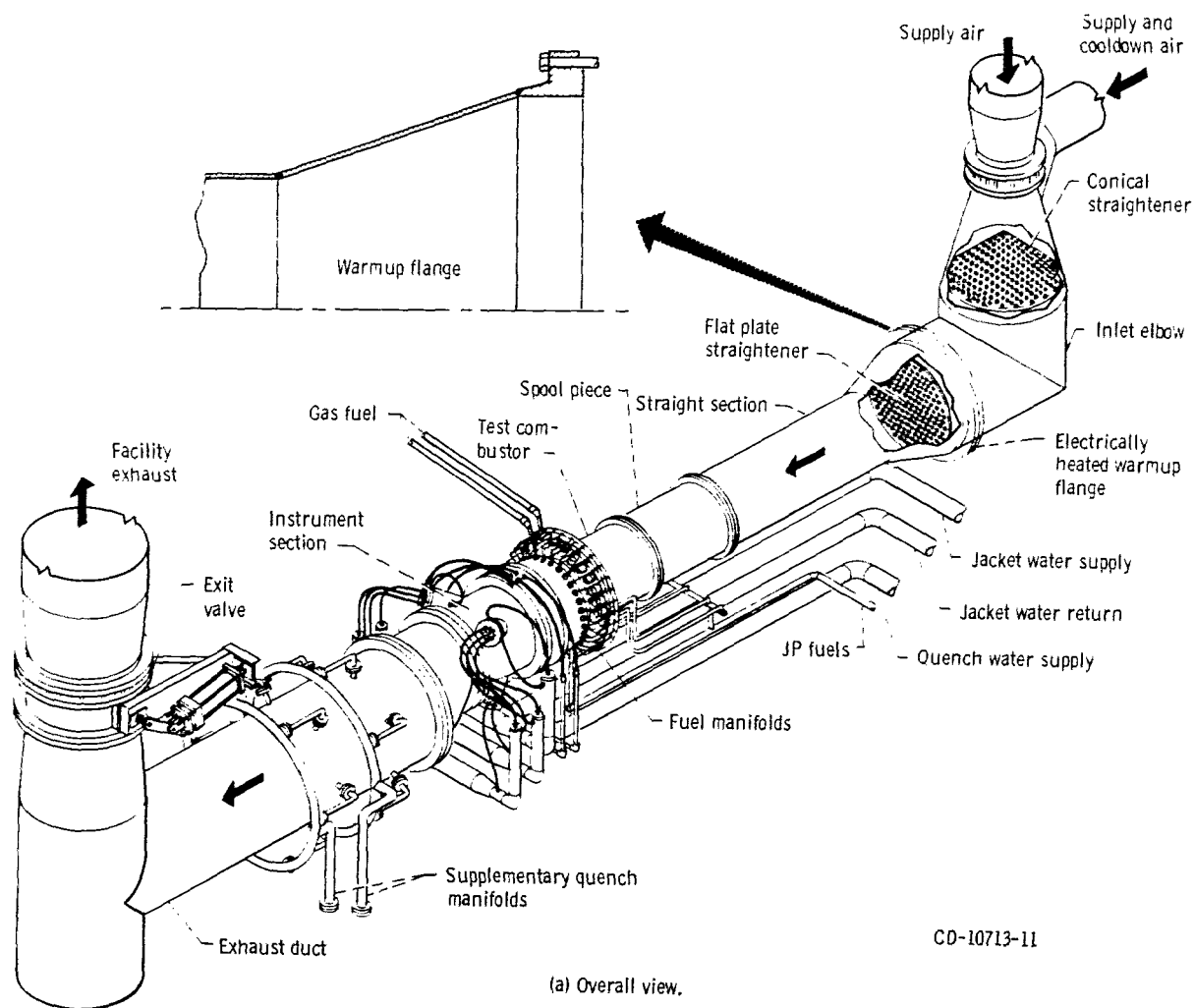
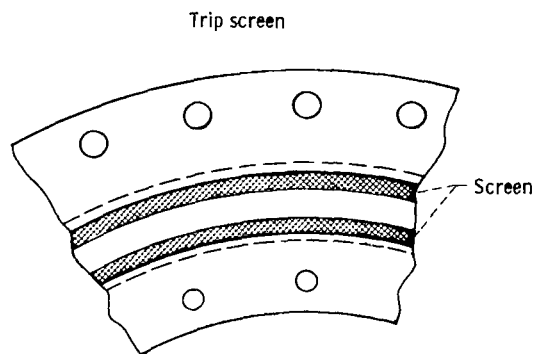
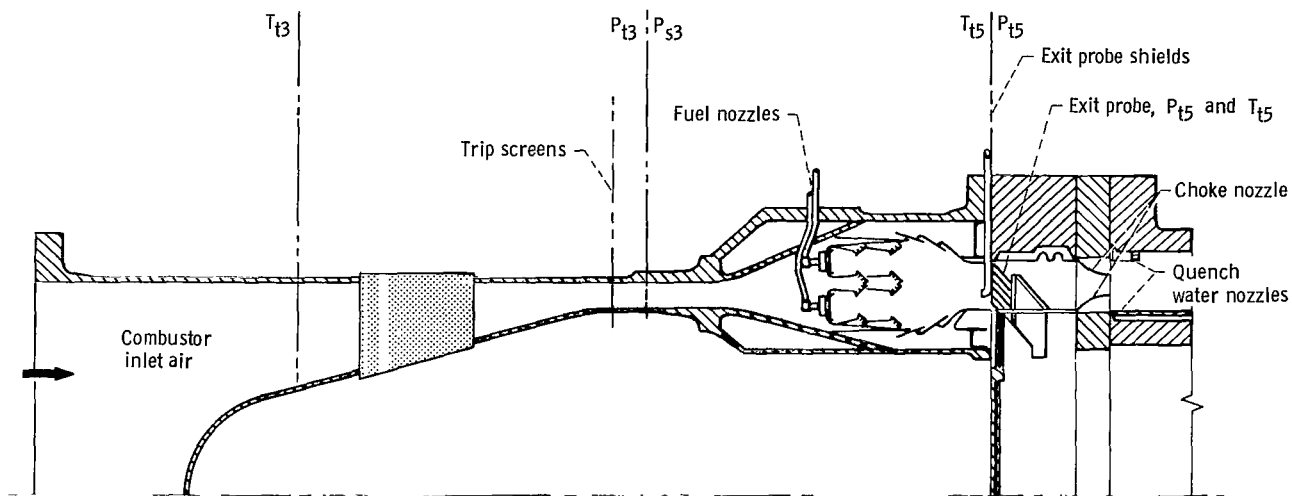
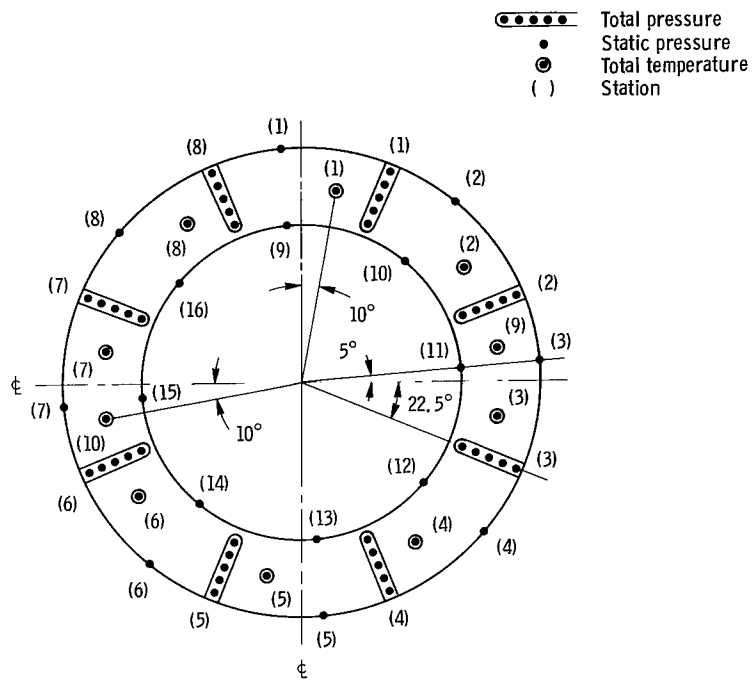


Figure 8. - Test section.



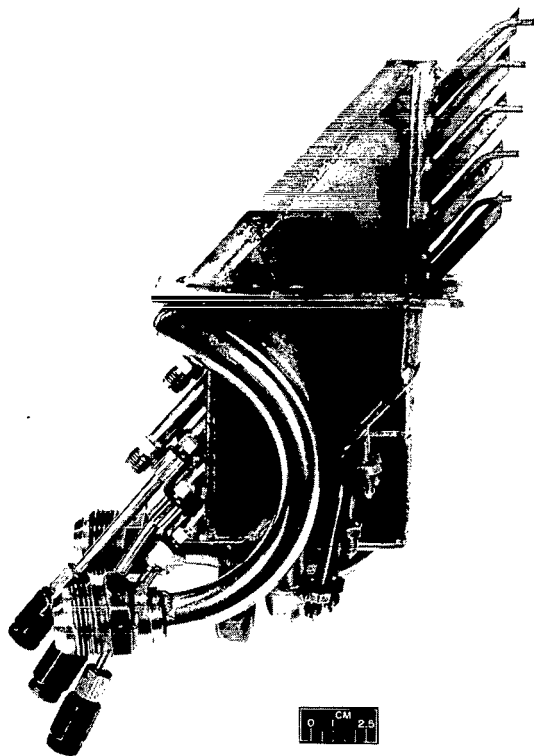
(b) Test combustor with trip screens.

Figure 8. - Continued.



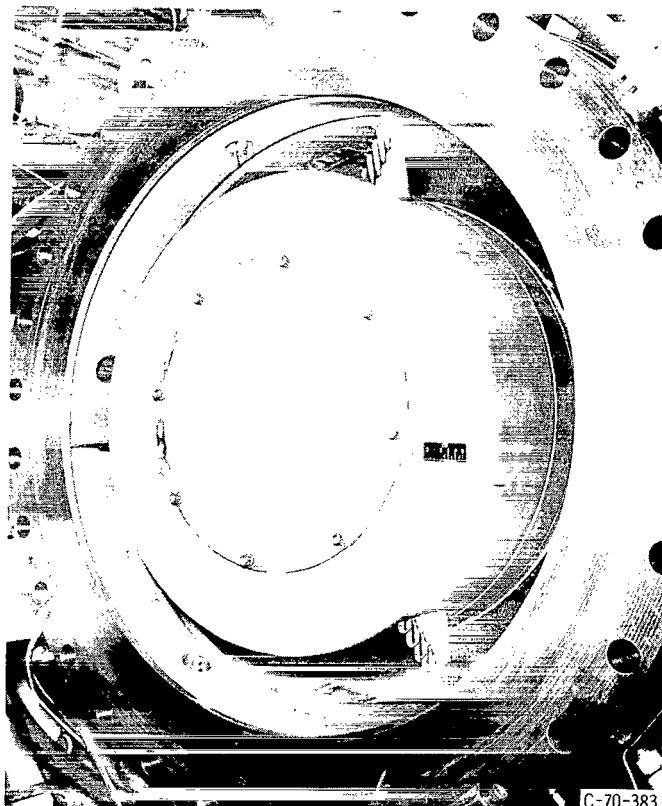
(c) Radial position of test combustor section instrumentation, looking downstream at station 3.

Figure 8. - Concluded.



(a) Probe head.

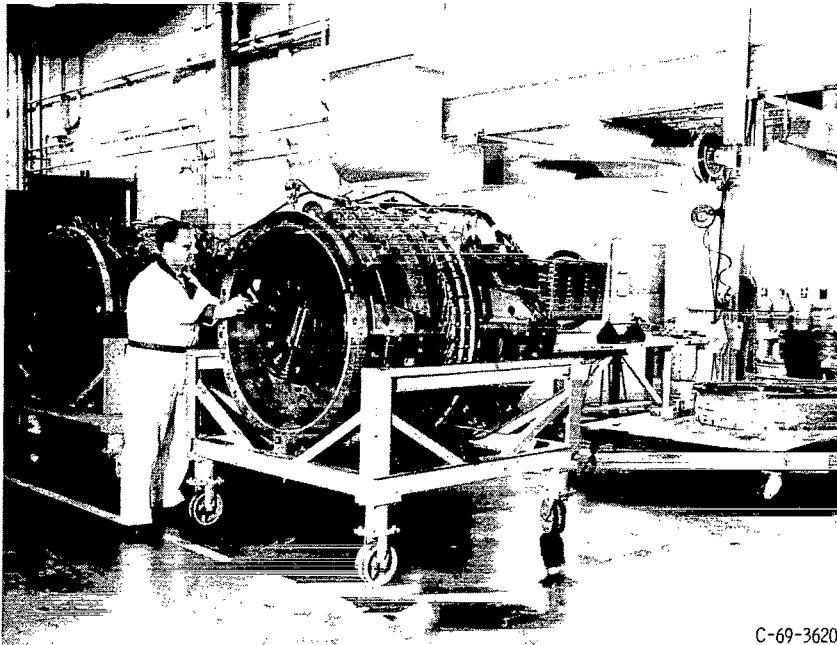
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(b) Probes mounted on drum.

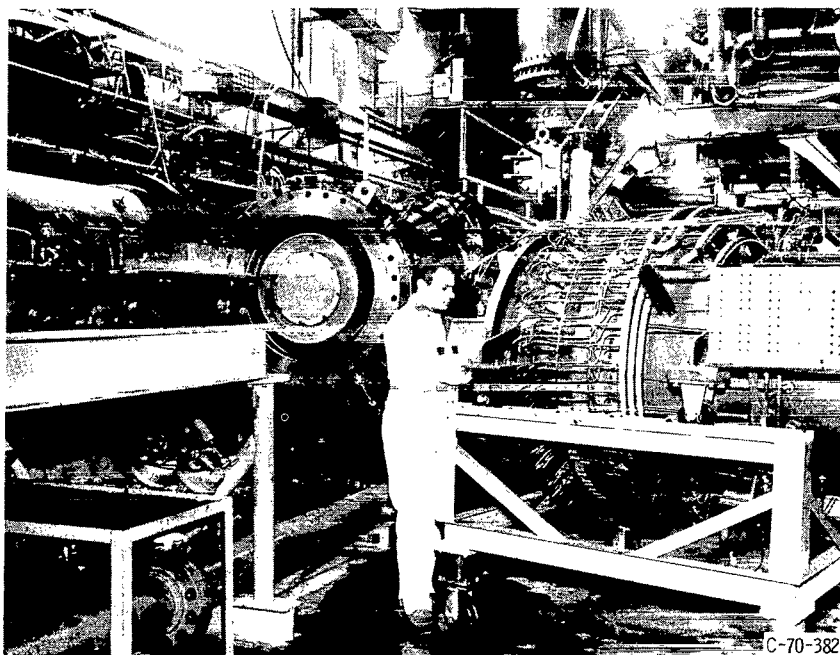
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Figure 9. - Combustor exit probes.



C-69-3620

Figure 10. - Test combustors in buildup.



C-70-382

Figure 11. - Test combustor installation.

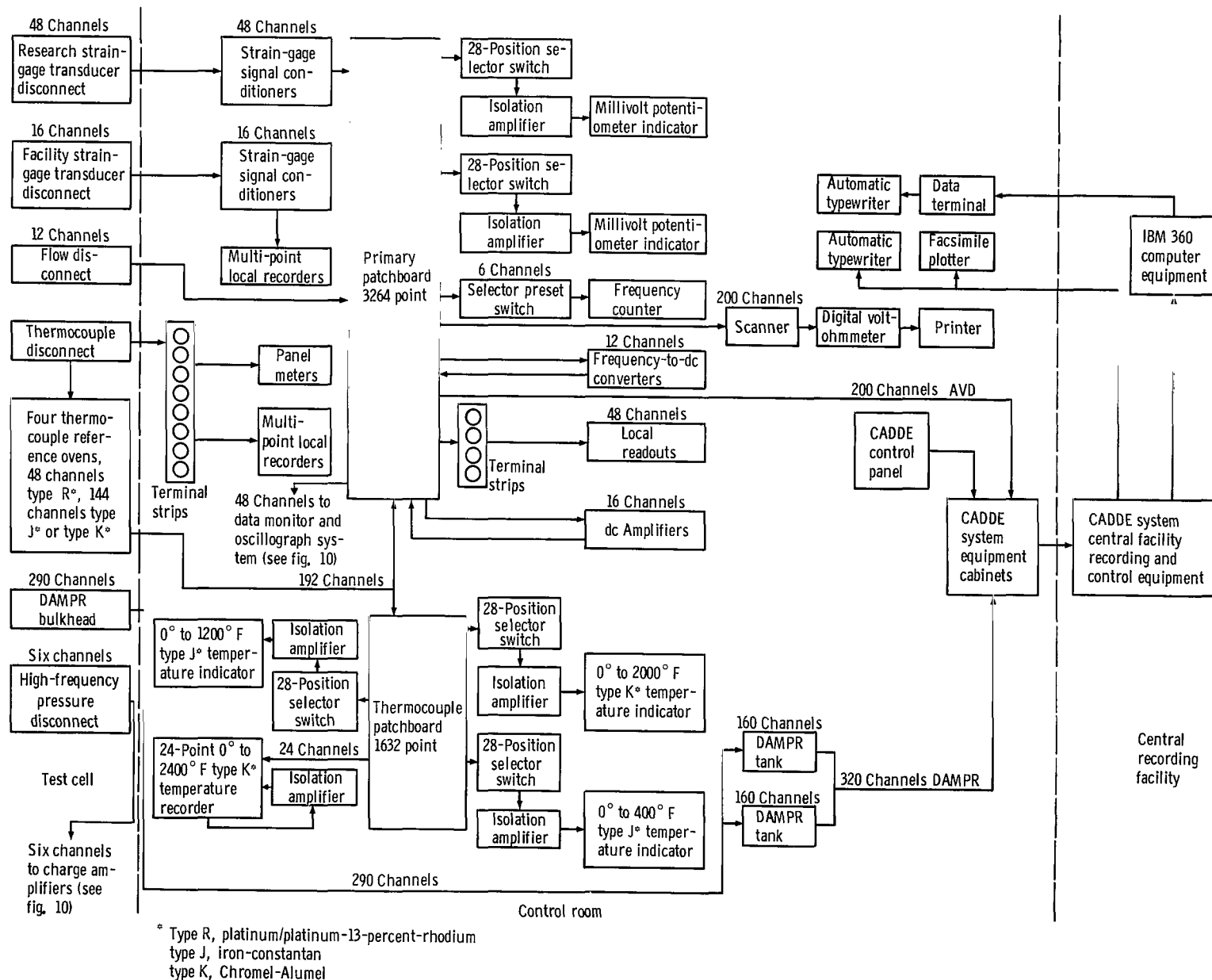


Figure 12. - Instrumentation system block diagram.

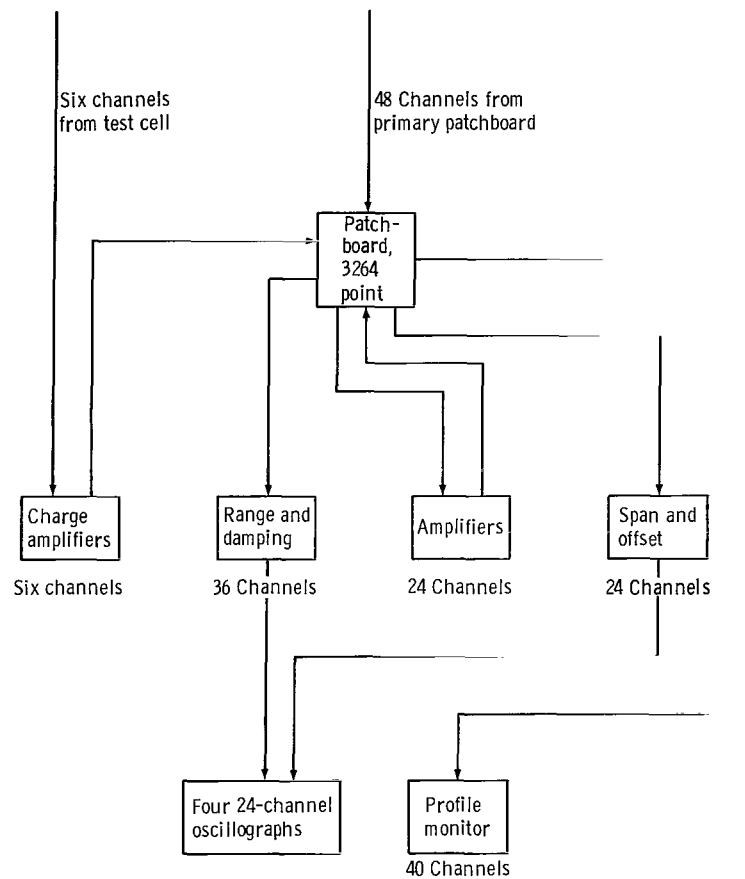
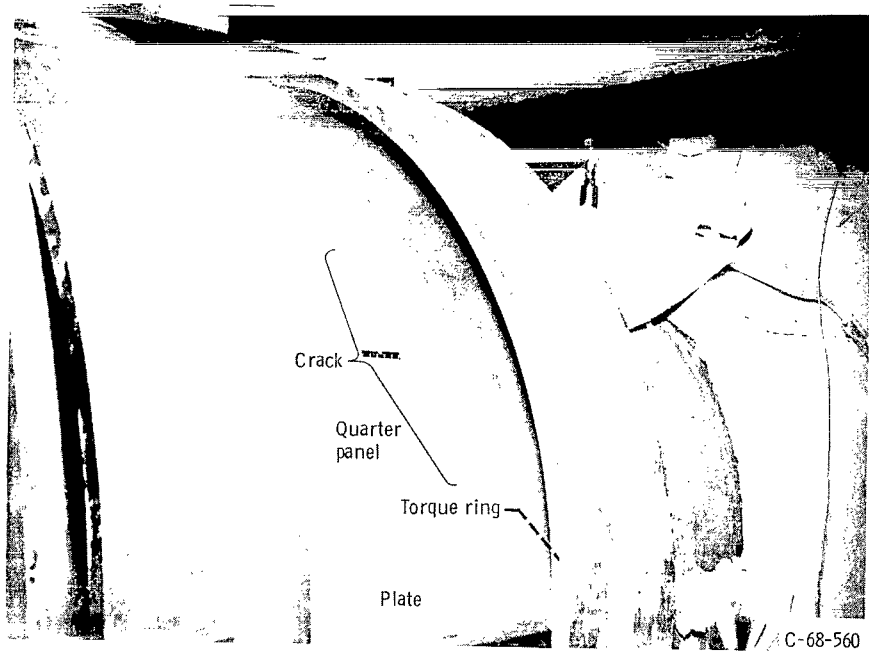
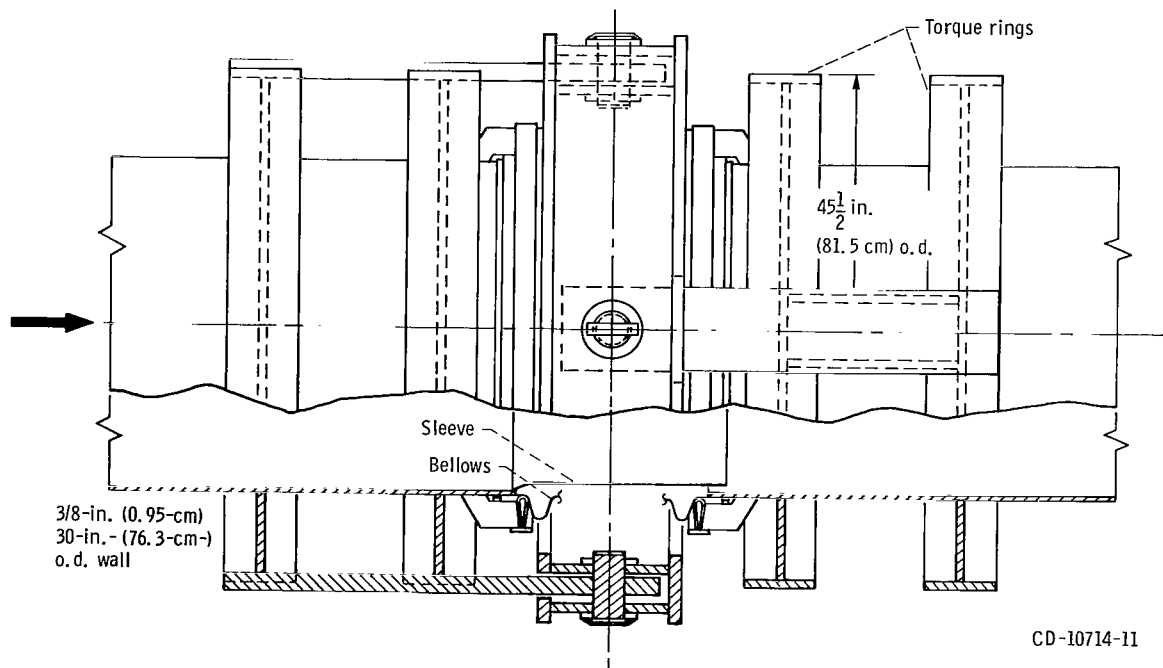


Figure 13. - Block diagram of analog recording and monitoring system.

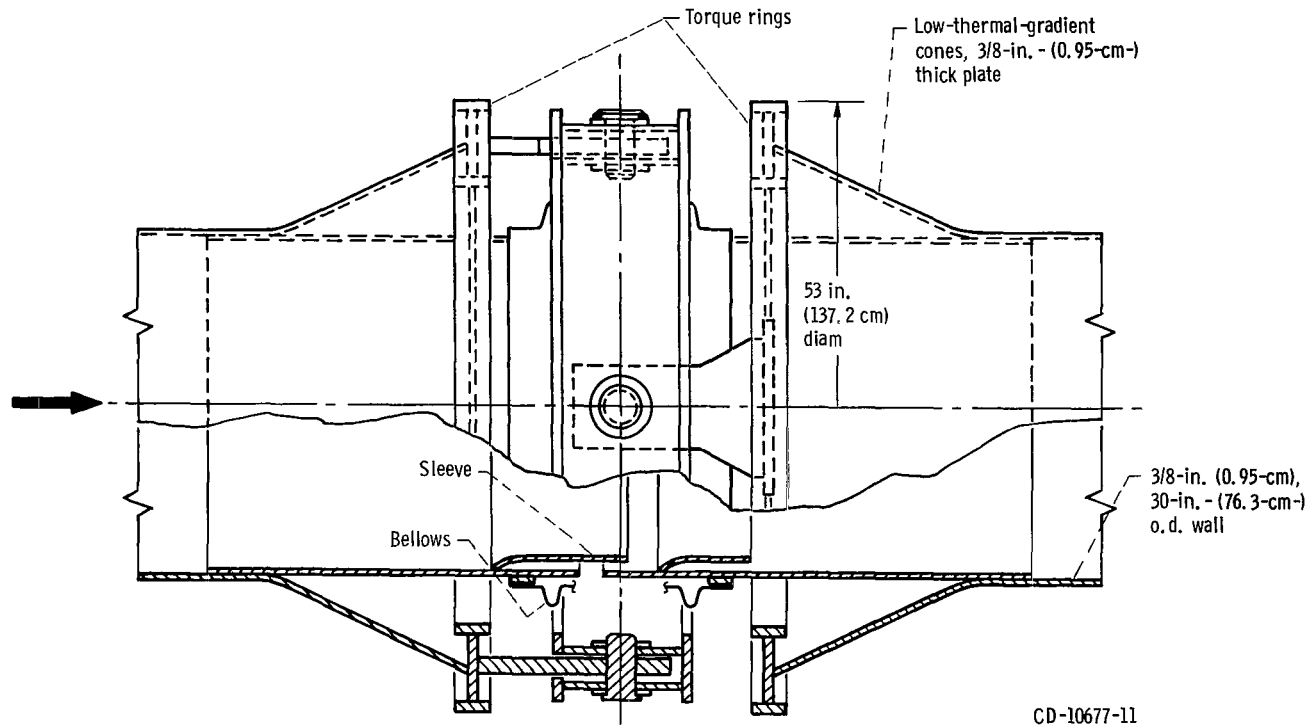


(a) Cracking of pipe in old assembly.



(b) Initial gimbal design.

Figure 14. - Gimbal joints.



(c) Present gimbal design.

Figure 14. - Concluded.

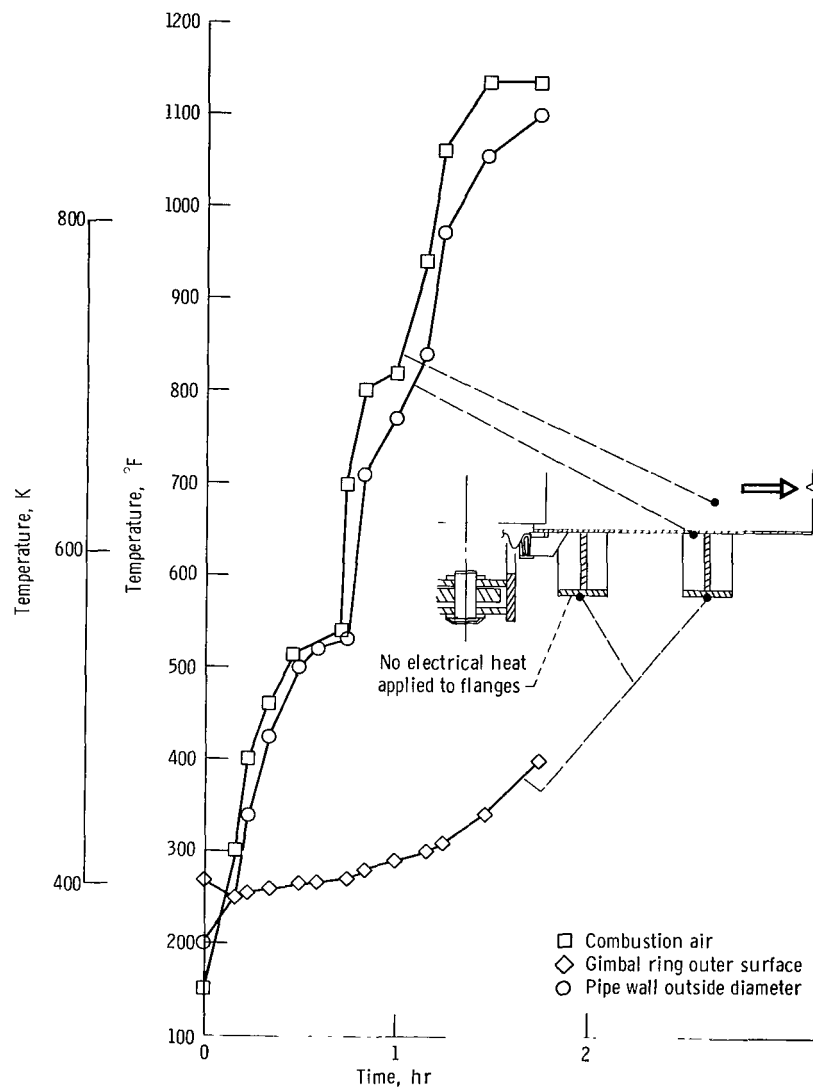


Figure 15. - Initial gimbal warmup.

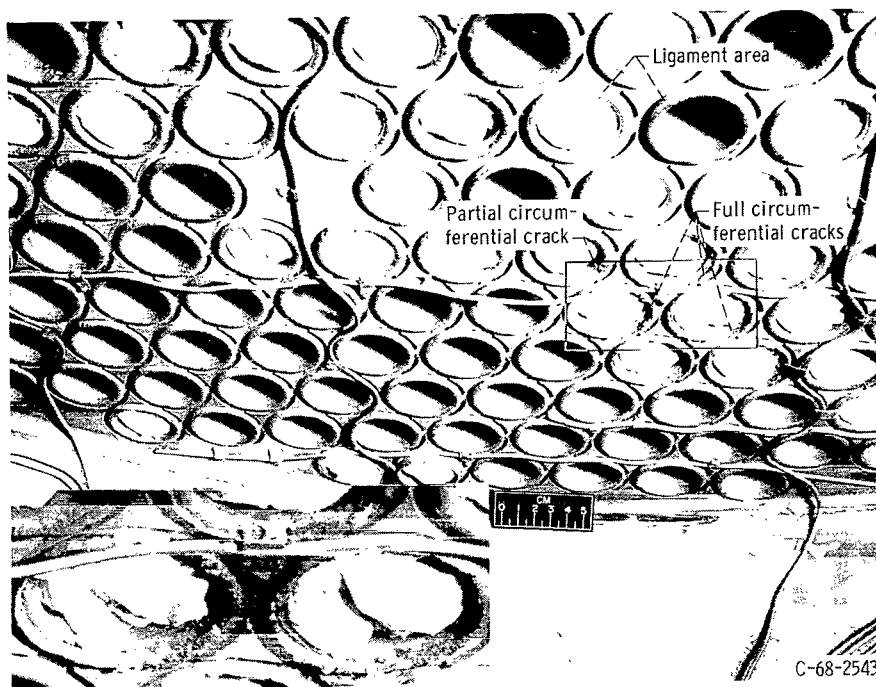


Figure 16. - Upstream face of tubesheet.

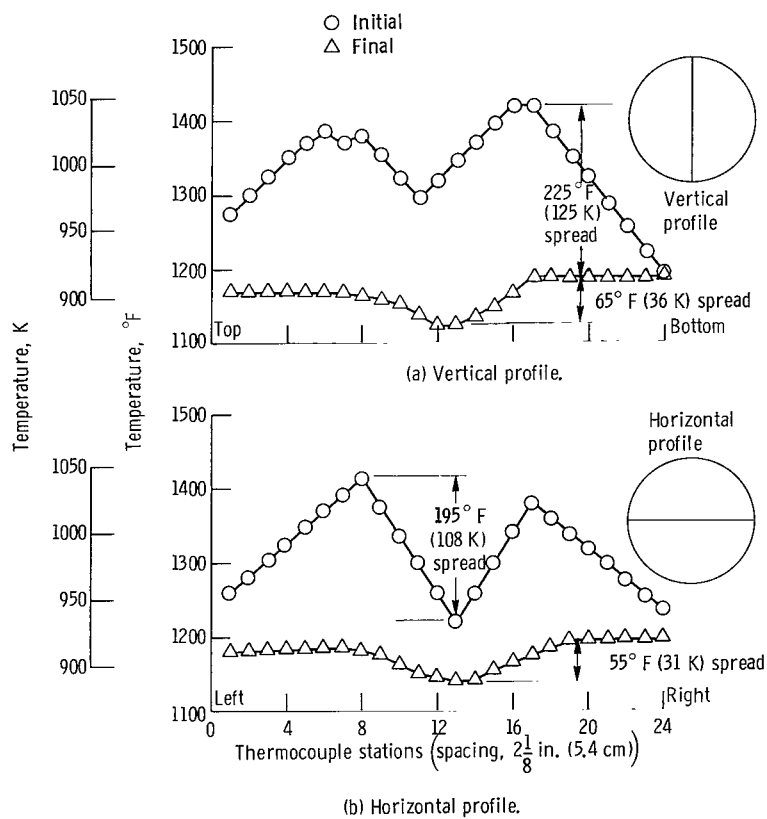
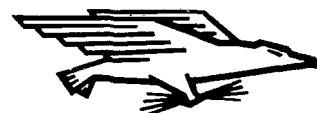


Figure 17. - Afterburner temperature profiles before and after modification.

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